

Probing Cosmic Strings with Satellite CMB measurements

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ABSTRACT: We study the problem of searching for cosmic string signal patterns in the present high resolution and high sensitivity observations of the Cosmic Microwave Background (CMB). This article discusses a technique capable of recognizing Kaiser-Stebbins effect signatures in total intensity anisotropy maps from isolated strings. We derive the statistical distributions of null detections from purely Gaussian fluctuations and instrumental performances of the operating satellites, and show that the biggest factor that produces confusion is represented by the acoustic oscillation features of the scale comparable to the size of horizon at recombination. Simulations show that the distribution of null detections converges to a χ^2 distribution, with detectability threshold at 99% confidence level corresponding to a string induced step signal with an amplitude of about $100 \mu\text{K}$ which corresponds to a limit of roughly $G\mu \sim 1.5 \times 10^{-6}$. We implement simulations for deriving the statistics of spurious detections caused by extra-Galactic and Galactic foregrounds. For diffuse Galactic foregrounds, which represents the dominant source of contamination, we construct sky masks outlining the available region of the sky where the Galactic confusion is sub-dominant, specializing our analysis to the case represented by the frequency coverage and nominal sensitivity and resolution of the Planck experiment. As for other CMB measurements, the maximum available area, corresponding to 7%, is reached where the foreground emission is expected to be minimum, in the 70-100 GHz interval.

KEYWORDS: Cosmology, CMB anisotropy, cosmic strings.

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1. Introduction

Current theories of particle physics predict spontaneous symmetry breaking in the early Universe, with the consequent creation of coherent structures in the spatial distribution of the fields involved in the process; these structures, known as topological defects, represent genuine tracers and unique remnants of those processes, occurring at energies which are not achievable with the current terrestrial particle colliders, see [3] and references therein. Among the most known and studied relics of this kind, cosmic strings correspond to an uni-dimensional region in which a (scalar) field is trapped by true minima of its potential, storing energy in that region. The energy density is parametrized by the dimensionless quantity $G\mu$ where G is the Newton's constant, and μ the string tension, see [3] for review. Years ago, while it was still unclear if strings could dominate the structure formation process, their signal was searched in the main statistical indicators of structure formation itself, like the power spectra of anisotropies in the Cosmic Microwave Background (CMB) or Large Scale Structure (LSS). The conclusion of these studies was that strings should contribute to cosmic structure formation by no more than a few percent [28, 34, 8, 4, 35, 30]. Indeed, the evidence for coherent acoustic oscillations in the CMB and LSS power spectra, dominated by density fluctuations, favored the scenario of isentropic or adiabatic Gaussian fluctuations like predicted in the simplest inflationary scenarios, and indicated that cosmic strings, if any, played a minor role in providing the initial conditions, in a statistical sense, to the Universe we see today. Early in their study, it was evident that strings produced perturbations that were not coherent as the observed acoustic oscillations and that they tend to produce equal power in scalar (density), vector (vorticity) and tensor (gravitational waves) perturbation modes. Recently, [30] proposed to look at sub-dominant, but most interesting components of the power spectrum of CMB anisotropies, namely the B modes

activated by cosmological gravitational waves, to constrain cosmic strings.

The hypothesis is then that these objects are washed away by inflation itself motivating the direct search of the signal from isolated and rare cosmic strings. Among these studies, those on CMB are based on the well known Kaiser-Stebbins effect [19] resulting in a step like feature in the CMB temperature caused by a string which is orthogonal and moving relativistically with respect to the line of sight. These studies produce upper limits on the abundance of string in our own observable Universe of course, but more quantitatively on the string density parameter $G\mu$ [16, 26, 17, 23, 29, 20, 9, 2, 25]. On the other hand, studies in the optical band look for strong lensing events, in which the strings bend the light from a distant Galaxy, causing a mirror image of that[33].

In this paper, we specifically search for signals imprinted on CMB temperature observations by long cosmic strings of cosmological scale, which was predicted by theory and also supported by simulations¹. The long strings between the last scattering surface and us would be back-lighted by CMB photons and leave signatures in CMB temperature map via the Kaiser-Stebbins effect. While the works mentioned above are dealing with the effects of cosmic string network on statistical observables, this work aims at the direct search of signals produced by isolated cosmic strings left on CMB temperature anisotropy maps, having a coherence length corresponding to at least the angle subtended by an Hubble horizon at decoupling. The Planck survey² of CMB temperature and polarization anisotropies is ongoing [24], promising a leap forward in many research fields, including constraints on cosmic strings abundance and tensions. The unprecedented frequency coverage, sensitivity and angular resolution requires a dedicated discussion targeted to the applicability and expectations from Planck direct searches of cosmic strings. In this paper we work out two missing issues concerning the direct search of KS effects of cosmic strings. The first one is represented by the statistics of null detections from pure Gaussian CMB anisotropies, with nominal noise and angular resolution of the operating satellites, which, needs to be quantified prior to data analysis. Consequently, as the second step, one can use the available models and data of Galactic and extra-Galactic foreground signal simulations at Planck frequencies, to select the sky area where false detections provide a negligible effect with respect to the main contaminant represented by the background, Gaussian and uniformly distributed, CMB anisotropies. In this paper we discuss and specialize the technique discussed in [17] to deal with these issues. In Section 2 we review in detail the effects of cosmic strings on the CMB temperature anisotropies and outline the string search algorithm. In Section 3, we apply the technique to simulated Planck data sets, quantifying the statistics of null detection based on the nominal performances of the satellite, as well as selecting the sky region which is available for searches based on the current knowledge of Galactic and extra-Galactic foreground emission. Concluding remarks are in Section 4.

2. Cosmic String effect on CMB and detection algorithm

Consider a cosmic string with mass per unit length μ , velocity β and direction \hat{s} both of

¹http://www.damtp.cam.ac.uk/research/gr/public/cs_evol.html

²www.rssd.esa.int/planck

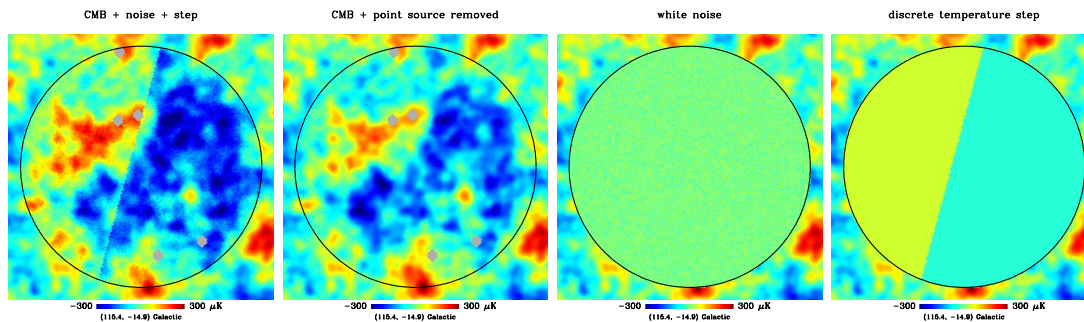


Figure 1: Decomposition of a patch of sky map which contains a discrete temperature step. The gray spots represent masked point sources. The discrete temperature step is slanted 15° from the polar axis. The instrumental noise was generated with power $\sigma_N = 10\mu\text{K}$ and the height of temperature step is $100\mu\text{K}$.

which are perpendicular to the line of sight, back-lighted by a uniform black body radiation background of temperature T . Due to the angular deflection $\delta = 8\pi G\mu$ in the conic space-time around the string, there is Doppler shift on photons passing around it on different sides, causing a temperature step across the string [19, 13] with magnitude given by

$$\frac{\delta T}{T} = 8\pi G\mu\gamma\beta, \quad (2.1)$$

where $\gamma = 1/\sqrt{1 - \beta^2}$. In a matter dominated universe the projected angular length of string in the redshift interval $[z_1, z_2]$ scales as $\sqrt{z_1} - \sqrt{z_2}$. The standard cosmological model ($\Omega_{DE} \sim 0.7$, $\Omega_m \sim 0.3$) places the decoupling of the CMB, also known as last scattering, at an epoch which corresponds to a redshift $z_{ls} \sim 1100$. The apparent angular size of the CMB horizon at last scattering is therefore given by

$$R = \frac{1}{\sqrt{z_{ls}}} = 1.8^\circ \left(\frac{1000}{z_{ls}} \right)^{1/2} \sim 1.7^\circ. \quad (2.2)$$

Thus, a convenient choice for the angular size of patches to be examined for cosmic string signature through (2.1) is simply the angle subtended by the CMB horizon at decoupling, as the maximum extent of the conic space-time formed around the string would be limited within the horizon at decoupling. The largest causally connected patch possible would be optimal in this pattern search, because a gradient or step-like pattern generated by white noise would be suppressed by $\sim 1/\sqrt{N_{\text{pixel}}}$ factor, and our choice the size of a test patch as the horizon size at the decoupling can be justified. The anisotropy in the CMB temperature sky map is caused by several processes including intrinsic perturbations in the photon fluid, metric fluctuations, possibly topological defects like cosmic strings. CMB photons pick up secondary anisotropies when traveling across forming structures on the line of sight toward us. Foreground anisotropies are caused by the emission from extra-Galactic point sources and our own Galaxy. Finally, the instrument adds instrumental noise and various systematics. By considering intrinsic CMB anisotropies, noise and the string contribution, one has

$$T_{\text{pixel}} = T_{\text{CMB}} + T_{\text{noise}} + T_{\text{step}}. \quad (2.3)$$

We employ five parameters which characterize a circular patch of string embedded sky map, T_0 , σ_G , Δ , p and α [18]. They represent the background uniform CMB temperature, the sum of the CMB anisotropy and noise variances, the amplitude of the discrete temperature step, the ratio of the blue-shifted pixels with respect to the total, and the orientation of the step, respectively. To recover these parameters from a given CMB region to be examined, where the individual components are superimposed, we define five observables which can be expressed in terms of $(T_0, \sigma_G, \Delta, p, \alpha)$:

$$\text{mean } \mu \equiv \frac{1}{\pi R^2} \oint T dA \quad (2.4)$$

$$\text{variance } \sigma^2 \equiv \frac{1}{\pi R^2} \oint (T - \mu)^2 dA \quad (2.5)$$

$$\text{dipole moment } \mathbf{D} \equiv \frac{1}{(\pi R^2)^{3/2}} \oint T \cdot \mathbf{r} dA \quad (2.6)$$

$$\text{inertia moment } I \equiv \frac{1}{(\pi R^2)^2} \oint T \mathbf{r}^2 dA \quad (2.7)$$

where the integrations are done over the examined sky area, chosen circular for simplicity, with radius R corresponding to the angular size of the horizon at decoupling, as we mentioned above. When a discrete temperature step is present and all the other components are suppressed, the observables defined in (2.4) - (2.7) can be analytically computed and expressed in terms the five step parameters:

$$\mu_\Delta = \Delta \left(p - \frac{1}{2} \right) \quad (2.8)$$

$$\sigma_\Delta^2 = \Delta^2 p (1 - p) \quad (2.9)$$

$$D_\Delta = \frac{2\Delta}{3\pi^{3/2}} \left(1 - \frac{x_c^2}{R^2} \right)^{3/2} \quad (2.10)$$

$$I_\Delta = \frac{\Delta}{\pi^2} \left[\frac{x_c}{3R} \left(1 - \frac{x_c^2}{R^2} \right)^{\frac{3}{2}} + \pi \left(p - \frac{1}{2} \right) \right] \quad (2.11)$$

where the discrete temperature step can be written as

$$T_{\text{step}} = \Delta \left[\theta(x - x_c) - \frac{1}{2} \right], \quad (2.12)$$

and x_c ($-R < x_c < R$) is the x -coordinate of the step with x -axis running normal to the temperature step, and $\theta(x - x_c)$ represents a step function. The relation between p (red-shifted area/total area) and x_c (coordinate of discontinuity) is given by

$$p = \frac{1}{2} - \frac{x_c}{\pi R} \sqrt{1 - \frac{x_c^2}{R^2}} - \frac{1}{\pi} \sin^{-1} \left(\frac{x_c}{R} \right). \quad (2.13)$$

The expressions for the observables (2.8) - (2.11) can be used to find the step parameters by solving for them, recovering the input ones. Now, taking into account the presence of

the non-string CMB fluctuations and noise, the observables can be calculated to the first order in the step parameters:

$$\mu = T_0 + \Delta \left(p - \frac{1}{2} \right) \quad (2.14)$$

$$\sigma^2 = \sigma_{\text{CMB}}^2 + \sigma_N^2 + \Delta^2 p(1-p) \quad (2.15)$$

$$D = |\mathbf{D}| = \frac{2\Delta}{3\pi^{3/2}} \left(1 - \frac{x_c^2}{R^2} \right)^{3/2} \quad (2.16)$$

$$I = \frac{T_0}{2\pi} + \frac{\Delta}{\pi^2} \left[\frac{x_c}{3R} \left(1 - \frac{x_c^2}{R^2} \right)^{\frac{3}{2}} + \frac{\pi p}{2} - \frac{1}{4} \right] . \quad (2.17)$$

At this point, we solve for the temperature step parameters (α (orientation), T_0 (uniform background temperature), x_c (location of temperature step), Δ (height of temperature step), $\sigma_G^2 = \sigma_{\text{CMB}}^2 + \sigma_N^2$) in terms of observables:

$$\alpha = \text{Im} \left[\ln \left(\frac{D_x + iD_y}{D} \right) \right] \quad (2.18)$$

$$\frac{x_c}{R} = \frac{1}{\sqrt{\pi}} \frac{2\pi I - \mu}{D} \quad (2.19)$$

$$\Delta = \frac{2\pi^{3/2}}{3} D \left(1 - \frac{x_c^2}{R^2} \right)^{-3/2} \quad (2.20)$$

$$T_0 = \mu - \Delta \left(p - \frac{1}{2} \right) \quad (2.21)$$

$$\sigma_G^2 = \sigma_{\text{CMB}}^2 + \sigma_N^2 = \sigma^2 - \Delta^2 p(1-p) . \quad (2.22)$$

Note that we use p and x_c interchangeably since they are related by (2.13). Expressions (2.18) - (2.22) are the key formulas in the algorithm used to compute the step parameters in any give horizon sized circular patch of the sky. Due to the presence of CMB and noise fluctuations (and foreground emissions, to be considered next), the results will have statistical fluctuations. The dispersions of the outputs are the estimate for the error associated to the quantities measured by the algorithm discussed here.

3. String detection statistics and foreground effects for satellite measurements

In this section, we apply the search algorithm outlined in the previous section in order to examine two important aspects of string search for satellite CMB measurements. The latter are characterized by a wide sky area and frequency coverage, mapping in particular the Galactic foreground contamination to high accuracy in bands where it is dominant, as well as high angular resolution and sensitivity. When looking for string signatures, one has to characterize the statistics of null detections caused by a pure Gaussian spectrum of CMB anisotropies, in order to assess the probability that a given event is actually caused by a string and not by an ordinary CMB fluctuations; moreover, the spurious detections caused by foreground emissions have to be quantified and controlled. In this Section we address both aspects.

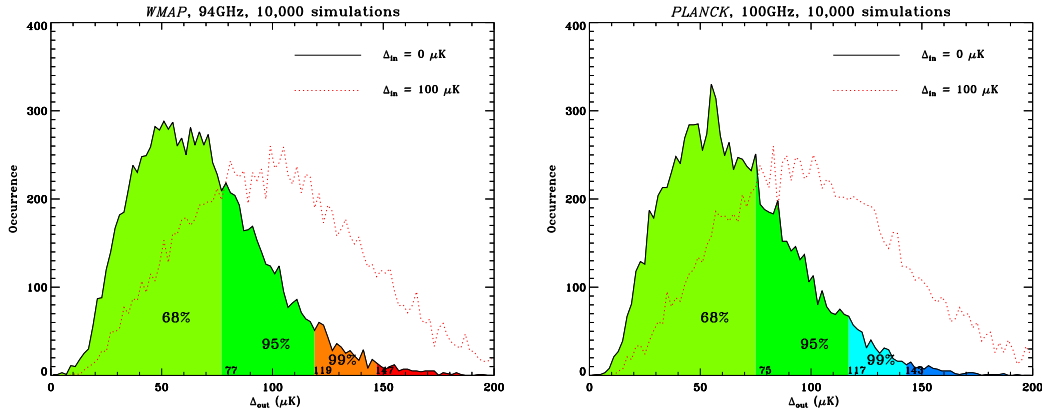


Figure 2: Simulation results with *WMAP* (left) and *PLANCK* (right) level simulated CMB temperature maps. Red-dotted curves are results with $\Delta_{\text{in}} = 100\mu\text{K}$.

	$C_{l \leq 140}, \sigma_N = 10\mu\text{K}$			$C_{l > 140}, \sigma_N = 10\mu\text{K}$		
Cumulative occurrence	68%	95%	99%	68%	95%	99%
$N_{\text{side}} = 2^9$	67	109	139	29	41	51
$N_{\text{side}} = 2^{10}$	67	109	141	29	41	49
$N_{\text{side}} = 2^{11}$	69	113	141	27	41	49
	$C_{l \leq 140}, \sigma_N = 100\mu\text{K}$			$C_{l > 140}, \sigma_N = 100\mu\text{K}$		
Cumulative occurrence	68%	95%	99%	68%	95%	99%
$N_{\text{side}} = 2^9$	71	109	135	35	49	59
$N_{\text{side}} = 2^{10}$	67	109	135	29	43	51
$N_{\text{side}} = 2^{11}$	67	109	131	29	41	49

Table 1: Comparison of cumulative occurrence levels of confusion outcomes for large and small scale CMB anisotropy power, with varying noise amplitude, map resolution.

3.1 Null detections from Gaussian CMB anisotropies

We use the publicly available simulation codes CAMB³ and HEALPix⁴ [12] to generate simulation maps with a consensus Λ Cold Dark Matter (Λ CDM) cosmology input parameters ($\Omega_b = 0.046$, $\Omega_{\text{CDM}} = 0.233$, $\Omega_\Lambda = 0.721$, $h = 0.701$) (see [21] for updated results on cosmological parameters). We run the detection algorithm described in the previous Section on these maps, and evaluate the statistics of null detections, adopting the nominal performances of the currently operating *WMAP* and *PLANCK* satellites. Indeed, we do not expect significant differences in the two cases, as the signal we are looking for is mainly concentrated on the degree scale, where both instruments are substantially limited by cosmic variance. The results are shown in Figure 2, solid line with colored integral. On the left, the angular resolution and nominal sensitivity were set corresponding to the *WMAP* W band with central frequency at 94 GHz, FWHM=13.2 arc minutes, $N_{\text{side}} = 2^9$, white noise noise rms = $\sigma_N = 35\mu\text{K}$ on $0.3^\circ \times 0.3^\circ$. On the right, the angular resolution and sen-

³<http://camb.info/>

⁴<http://healpix.jpl.nasa.gov>

sensitivities were chosen correspondingly to the *PLANCK* 100 GHz channel on-board the High Frequency Instrument, with FWHM=10 arcmin, $N_{\text{side}} = 2^{11}$, noise rms = $\sigma_N = 2.5\mu\text{K}$ on squared pixels with side equal to the FWHM. The first thing to note is that the distributions of the null detected Δ_{out}^2 are similar as we anticipated, and approximately follow a χ^2 -distribution, due to the randomness of Gaussian peaks which determine the spurious signal. The color filled curves in Figure 2 show the different confidence level that a given event in a real measurement is not due to spurious detection from Gaussian anisotropies. For *WMAP*, 68% of occurrences falls in $0 < \Delta < 77\mu\text{K}$, 95% in $\Delta < 119\mu\text{K}$ and 99% in $\Delta < 147\mu\text{K}$, respectively. For *PLANCK*, we have 68% in $0 < \Delta < 75\mu\text{K}$, 95% in $\Delta < 117\mu\text{K}$ and 99% at $\Delta < 143\mu\text{K}$. The dotted lines also show the cases in which the sky signal was added with a step with $\Delta_{\text{in}} = 100\mu\text{K}$ in each area examined, clearly indicating that the search algorithm is working, as the distribution peaks at the chosen value of Δ_{in} . The fact that *WMAP* and *PLANCK* show nearly same results indicates that the effects of map resolution or instrumental noise level applied here on the result are nearly negligible compared to other factors, which we will discuss further in the following.

In conclusion of this Section, we show that the main contaminant for cosmic string search with specifications corresponding to the operating satellites are not given by the noise but by the underlying Gaussian fluctuations, which are dominated by acoustic oscillations on the degree scale which we are focusing on. In order to contrast the effects of super-horizon scale fluctuations and sub-horizon ones, we compute the statistics of null detections by considering simulated maps with anisotropy power on the super-degree angular scales ($l \leq 140$) and sub-degree ones ($l \geq 140$), separately. Notice that the rms fluctuation power is about the same for the two sets:

$$\sum_{l=2}^{140} \frac{2l+1}{4\pi} C_l = \sum_{l>140} \frac{2l+1}{4\pi} C_l. \quad (3.1)$$

In Table 1, one sees the variation of the confidence levels for the large and small scale power as a function of map resolution, noise level. At the first glance, it is clear that, while noise and map resolution do not induce significant differences, the most significant improvement is obtained when super-degree and degree scale power is taken out.

3.2 Spurious string signals from foregrounds

Foregrounds are considered as one of the ultimate limitation of CMB measurements, and represent a major source of contamination, in particular for cosmic string searches. Multi-frequency data analysis techniques are being studied for *PLANCK* [22], and applied successfully to the *WMAP* data [6] in order to separate them from the main CMB emission. Here we take a conservative approach, by exploiting the current foreground observations outside and inside the microwave band, performing an all sky analysis looking for regions where they cause spurious string detections, focusing on the *PLANCK* frequency channels going from 30 to 353 GHz.

Let us consider extra-Galactic point sources first. The usual technique to identify and remove them is to isolate 5σ events above the CMB and noise standard deviations, and

Frequency	Cumulative occurrence (μK)		
	68%	95%	99%
30 GHz	69	109	133
44 GHz	73	115	141
70 GHz	75	117	143
100 GHz	77	119	147
143 GHz	77	119	145
217 GHz	77	119	147
353 GHz	77	119	147

Table 2: Cumulative occurrences of string signal detection from the simulated full sky CMB maps of 7 *PLANCK* frequencies. For each frequency band, smoothing and instrumental noises are applied accordingly as specified in [27].

removing them with optimal filters [15]. Residual sources behave as a correlated noise due to beam smoothing which remains in the maps. We simulated randomly scattered point sources according to the existing modeling of the radio and infrared populations [5, 11]. After removing the 5σ signals, causing typically a few holes of beam size in the patches we consider, we run our cosmic string search algorithm to look for spurious detections. By comparing the recovered spurious Δ , we find that no significant disturbance from unresolved point sources is observed, due to their sub-dominance with respect to the CMB acoustic oscillations, which largely prevails as a contaminant.

The situation is markedly different for the diffuse foregrounds coming from our own Galaxy. We construct all sky maps including the effect of three of the main diffuse Galactic emission mechanisms: the synchrotron emission is caused by electrons spiraling around the lines of the Galactic magnetic field, using the data by [14], treated by [10] with spectral index obtained from WMAP analysis [1], see for more detail⁵; the dust total intensity is based on the analysis of IRAS and DIRBE data by [7], implementing model 8 of frequency scaling including spatial variations of dust frequency scaling; the free-free emission from Brehmstraahlung of electrons hitting ions in the Galaxy, traced by $\text{H}\alpha$ emission, has also been included⁶.

We simulate sky maps with these emissions included at 30, 44, 70, 100, 143, 217 and 353 GHz, and apply the cosmic string detection algorithm. As expected, we do find regions with high rate of contamination, concentrated close to the Galactic plane, at all frequencies. We show the results in Figure 3, where we show all together the regions yielding spurious cosmic string signals with various confidence levels based on the distribution of null detection from CMB emission only, outlined in Table 2. Notice that, in addition to the Galactic plane signals, several emissions are noticeable from intensely emitting Galactic clouds at intermediate latitudes. Cosmic string searches based on the algorithm presented here should be avoided in the highlighted regions.

⁵<ftp://ftp.rssd.esa.int/pub/synchrotron/README.html>

⁶<http://astrometry.fas.harvard.edu/skymaps>

4. Conclusions

We studied a direct cosmic string search based on the Cosmic Microwave Background (CMB) anisotropies in total intensity, in the context of the existing satellite observations, focusing on the case of the ongoing *PLANCK* survey. The search algorithm uses an algebraic method to detect step like structures in CMB maps, caused by the Kaiser-Stebbins effect induced by strings moving on the orthogonal plane with respect to the line of sight. We quantified two important aspects towards the application of this algorithm to the actual data.

First, we derived the statistics of null detections due to instrumental noise and purely Gaussian CMB anisotropies as predicted within the Λ Cold Dark Matter (Λ CDM) cosmology. We have shown that the biggest cause of confusion for the detection algorithm is caused by the CMB acoustic oscillations at wavelengths comparable to the size of the horizon at decoupling, while noise and angular resolution which are typical of the operating satellites, are less important. The distribution of null detection converges to a χ^2 -distribution. We derived the confidence levels of detection of cosmic strings in *PLANCK* maps by estimating the 68%, 95% and 99% of cumulative occurrence of null detection, thresholds give in Table 2, which corresponds to $G\mu \sim 1.5 \times 10^{-6}$ for 95% of occurrences in terms of cosmic string tension, according to the relation between the string tension and temperature shift of CMB photons in 2.1.

On the basis of these results, we were able to evaluate the effect of extra-Galactic and Galactic foreground emissions on cosmic string searches, by comparison the foreground induced string signals with the detectability threshold found in the first part of this work. As expected, we find that after removal of the brightest sources exceeding 5σ times the CMB rms, residual confusion due to unresolved point sources does not have a significant impact on the string detection algorithm. On the other hand, the diffuse Galactic emission from our own Galaxy do cause false detection in a significant fraction of the sky, not because of their overall intensity, but rather due to their gradients, reaching intermediate Galactic latitudes. By using the current data and models of the diffuse Galactic emissions based on off microwave band data as well as the measurements of the *WMAP* satellite, we determine the area of the sky where false detection are expected due to the Galactic emission, at the level of 68%, 95% and 99% of cumulative occurrences for each of seven *PLANCK* frequencies, where the thresholds are given in Table 2. We specialize the discussion to seven frequency channels on-board *PLANCK*, constructing for each one the sky mask to be used for string searches. The maximum available area in which the Galactic contamination is sub-dominant with respect to the contribution from Gaussian CMB fluctuations is found in the frequency interval 70-100 GHz, and represents about 7% of the entire sky. These criteria and findings can be used in the actual application of string searches in CMB data. For the future work on the pattern search of cosmic strings in CMB temperature data, it is desirable to exploit the correlated signals of discrete steps lined up close to each other, since the pattern search is mainly pointed at the long strings of cosmological scale rather than isolated segments or loops of cosmic strings. The methodology provided in this paper on finding step signal by a cosmic string segment will be the basis for the long string search.

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References

- [1] Bennett, C. L., et. al., 2003, ApJS, 148, 97B
- [2] Christiansen, J. L., et. al., 2008, Phys.Rev.D, 77, 123509
- [3] Copeland, E. & Kibble, T. W. B., 2009, arXiv:0911.1345v2
- [4] Davis, A.-C. & Kibble, T.W.B, 2005, Contemp.Phys, 46, 313
- [5] De Zotti G., Ricci R., Mesa D., Silva L., Mazzotta P., Toffolatti L., González-Nuevo J., 2005, A&A, 431, 893
- [6] Dunkley, J., et. al, 2008, arXiv:0811.3915v2 [astro-ph]
- [7] Finkbeiner, D. P., et. al., 1999, ApJ 524, 867
- [8] Fraisse, A., JCAP 0703:008, 2007
- [9] Gasparini, M. A. et. al., 2008, MNRAS 385, 1959
- [10] Giardino, G., et. al., A & A 387, 82
- [11] González-Nuevo, J., Toffolatti, L., & Argüeso, F. 2005, ApJ, 621, 1
- [12] Gorski, K. M., et. al., 2005, ApJ 622
- [13] Gott, J.R., 1985, Ap. J. 288, 422
- [14] Haslam, C. G. T., et. al., 1982, A& AS, 47, 1H
- [15] Herranz, D., et. al, 2009. arXiv:0808.2884v1 [astro-ph]
- [16] Hindmarsh, M., 1994, ApJ, 431, 534
- [17] Jeong, E. & Smoot, G. F., 2005, ApJ, 624, 21
- [18] Jeong, E., & Smoot, G. F., 2007, ApJL. 661, L1
- [19] Kaiser, N., & Stebbins, A., 1984, Nature 310, 391
- [20] Kuijken, K. & Siemens, X. & Vachaspati, T, 2008, MNRAS 384, 161
- [21] Larson, D., et. al., 2010, arXiv:1001.4635
- [22] Leach, S. M., et. al, 2008, A& A 491, 597L
- [23] Lo, A. S. & Wright, E. L., 2005, astro-ph/0503120
- [24] Mandolesi, N., et. al., 2010, arXiv:1001.2657
- [25] Morganson, E. & Marshall, P. & Treu, T. & Schrabback, T. & Blandford, R. D., 2009, arXiv:0908.0602

⁷<http://lambda.gsfc.nasa.gov/>

⁸<http://healpix.jpl.nasa.gov/>

- [26] Perivolaropoulos, L. & Simatos, N., 1998, astro-ph/9803321
- [27] *PLANCK* Bluebook 2005, *PLANCK* collaboration
- [28] Pogosian et al., 2003, Phys.Rev.D, 68, 023506
- [29] Pogosian, L., Wasserman, I., & Wyman, M., 2006, astro-ph/0604141
- [30] Seljak, U. & Slosar, A., 2006, Phys.Rev.D, 74, 063523
- [31] Vachaspati, T., 1986, Nucl. Phys. B277, 593
- [32] Vilenkin, A., 1986, Nature 322, 613
- [33] Vilenkin, A. & Shellard, E. P.S., "Cosmic Strings and Other Topological Defects", 2000, Cambridge University Press, UK
- [34] Wu, J-H., 2005, astro-ph/0501239
- [35] Wyman, M., Pogosian, L., & Wasserman, I., 2005, Phys.Rev.D, 72, 023513

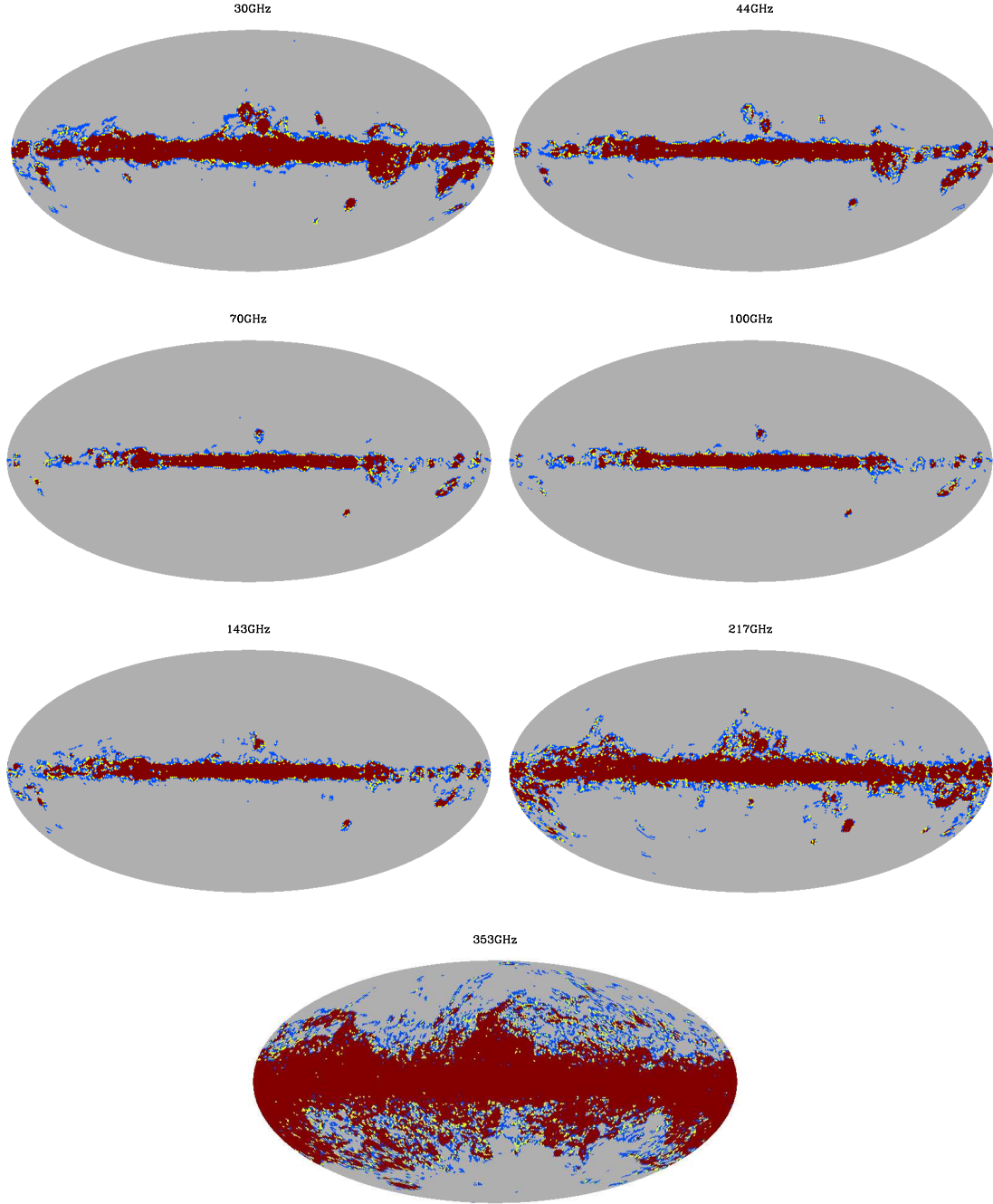


Figure 3: Area overshadowed by strong signals from diffuse foreground emissions for each of the 7 *PLANCK* frequencies considered, 30, 44, 70, 100, 143, 217 and 353 GHz. Blue, yellow and red colored areas denote the regions where the confusion outcomes by foreground emissions exceed 68%, 95% and 99% of cumulative occurrences from simulated CMB maps for each corresponding frequencies, which are shown in Table 2.